
Reionization of an Inhomogeneous Universe

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Abstract

Full radiative transfer in 3D space has been solved to pursue the reionization history in an inhomogeneous universe. It has been shown that the reionization of an inhomogeneous universe is not a prompt event, but a fairly slow process. Also, QSO absorption line systems are simulated with using the results of radiative transfer calculations. Ly α continuum depression implies that the metagalactic UV intensity decreases rapidly with z at $z > 5$, and the reionization must have taken place between $z = 6$ and 10. Finally, it is stressed that H α forest is a more powerful tool to probe the reionization history and the density fluctuations in the universe at $z > 5$.

1. Introduction

The cosmic reionization is one of the most significant issues in cosmology, which is closely related to the formation of QSOs and galaxies. The information on the ionization states in the universe has been accumulated by the observations of Ly α absorption lines in high redshift QSO or galaxy spectra. 3D cosmological hydrodynamic simulations (Cen et al. 1994; Miralda-Escude et al. 1996; Gnedin & Ostriker 1996; Zhang et al. 1997) have revealed that the Ly α absorption systems can be accounted for in terms of the absorption by intergalactic density fluctuations. However, all of these works have been based upon optically-thin or local optical-depth approximations. Recently, it has been shown that the radiative transfer effects of ionizing radiation could strongly affect the ionization structure (Razoumov & Scott 1999; Gnedin 1999; Nakamoto et al. 1999). Madau (1995) and Haardt & Madau (1996) as well have considered cosmological radiative transfer on the assumption of 1D semi-infinite slab. Here, we present 3D radiative transfer calculations on the cosmic reionization and the formation of QSO absorption line systems.

2. Method

To reproduce an inhomogeneous universe, we generate density fluctuations based upon the Zel'dovich approximation. In the present calculations, we assume a standard cold dark matter cosmology, i.e., $\Omega_{\text{CDM}} = 0.95$, $\Omega_{\text{Baryon}} = 0.05$, $\sigma_8 = 0.6$ with the Hubble constant of $50 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

We calculate the ionization degree by assuming the temperature of 10^4 K and ionization equilibrium. The simulation box is irradiated by the isotropic UV background radiation of a power law-type spectrum, $I_0 = I_{21} 10^{-21} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1}$. The so-called "proximity effect" of Lyman alpha absorption lines requires the diffuse UV radiation to be at a level of $I_{21} \approx 1$ at $2 < z < 4$ (Bajtlik, Duncan, & Ostriker 1988; Giallongo et al. 1996).

The UV radiation fields are obtained by solving the three-dimensional steady radiative transfer equation. For the implementation of the radiative transfer on a massively parallel supercomputer, we have developed a new scheme 'Sequential Wave Front Method'. We have used 128^3 grids in space, 128^2 in directions, and 6 for important line frequencies of hydrogen and helium. Since the continuum is analytically integrated, the calculations are quite accurate even if just 6 frequencies are solved. The total operations amounts to about 1 Tflops*hour. The calculations have been performed on the CP-PACS in University of Tsukuba.

3. Results & Discussion

3.1. Cosmic Reionization

Around $z = 15$, underdense regions are reionized and percolate, leaving overdense neutral islands due to the self-shielding effects. Since the absolute density decreases with time in a linear regime of density fluctuations, the reionization proceeds and the ionized sea encroaches onto the neutral islands, leaving filamentary self-shielded regions at $z \sim 9$. The highly ionized regions expand further at $z \sim 7$, but the universe is not perfectly transparent against UV radiation in the sense that the collective optical depth considerably reduces the incident radiation. Around $z = 5$, the universe becomes transparent against background UV and the overall reionization has been fulfilled. The simulations have revealed that, owing to the radiative transfer effects, the reionization in an inhomogeneous universe is not a prompt event, but a fairly slow process, in contrast to the prompt reionization in a homogeneous universe.

3.2. $\text{Ly}\alpha$ Absorption Lines and Continuum Depression

The resultant ionization degrees in the universe are different from place to place by more than three orders of magnitude. Due to such inhomogeneous ionization structure, relatively low ionization regions could produce strong absorption in quasar spectra. To make a direct comparison with the observations, we simulate absorption lines. First, we focus on $\text{Ly}\alpha$ absorption. To match the recent observations by the Keck telescope, we adopt the resolution of $R=45000$ and the variance of 0.04, and assume the Voigt profile of lines. The simulated $\text{Ly}\alpha$ absorption features are shown in Figure 1.

Fig.1 – The simulated $\text{Ly}\alpha$ absorption lines against wavelength at $z = 3$ (*top panel*) with $I_{21} = 1$, $z = 4$ (*second*) with $I_{21} = 0.1$, and $z = 5$ (*third*) with $I_{21} = 0.01$. The bottom panel is the diagram of $\text{Ly}\alpha$ continuum depression (*thick gray curves*) against redshifts. Symbols are observations. Also, the mean neutral fractions X_{HI} (*thin curves*) are shown. The same line types correspond to the same UV intensity.

Fig.2 – Same as Fig. 1, but for the $\text{H}\alpha$ absorption. There are no observation data so far for $\text{H}\alpha$ absorption at high redshifts

In order to compare quantitatively the simulations with observations, we have assessed the so-called continuum depression, D_A . Figure 1 shows that any model with a constant UV intensity does not match the observed trend that D_A tends to grow quickly at higher redshifts up to 5. This implies that the metagalactic UV intensity must decrease rapidly with z at $z > 5$ by two orders of magnitude at least. If the well fitted value of $I_{21} = 0.01$ at $z = 5$ is unchanged also at higher redshifts, the reionization epoch is estimated to be $z \approx 9$. If the UV intensity decreases in a similar fashion also at higher redshifts, the reionization epoch is $z \approx 6$. Thus, it is concluded that the cosmic reionization must have taken place between $z = 6$ and 10. However, the $\text{Ly}\alpha$ absorption is not appropriate to determine the reionization epoch more accurately, because, as seen in the

absorption features in Figure 1, Ly α is too strongly depleted even if the mean neutral fraction is less than 10^{-2} . In other words, D_A is no longer sensitive to X_{HI} around the cosmic reionization epoch.

3.3. H α Forest

As shown in the previous subsection, Ly α has too high line opacity to probe the universe at $z > 5$. Therefore, three conditions are required for a line in order to investigate the universe at $z > 5$: (1) it has lower line opacity than Ly α , (2) line emission is detectable, and (3) it has lower extinction against dust because young star-forming galaxies are often dust-enshrouded. The most favorable solution is H α absorption lines. In Figure 2, the H α absorption features and continuum depression are shown. The H α absorption is relatively weak around $z = 3$, while it is sensitive to the ionization degrees at $z > 4$. Also the H α continuum depression traces the reionization history more accurately. Therefore, it is concluded that H α forest is a more powerful tool to probe the universe at $z > 5$. H α forest has been never detected so far. The reason comes from the fact that H α has much weaker opacity than Ly α . From observational points of view, the continuum depression can be detected by low-dispersion spectroscopy or narrow-band photometry. Furthermore, H α forest is subject to less UV bump effects for AGNs compared to Ly α forest. The wavelengths of H α forest drop on $3\mu\text{m} \lesssim \lambda_{H\alpha} \lesssim 7\mu\text{m}$ at $4 \lesssim z \lesssim 10$. Thus, the observations can be done with Subaru IRCS, IRIS, SIRTf, NGST, or H2/L2. If one can obtain the absorption features with the resolution greater than 10000, one can recover the density fluctuations at high redshifts. They allow us to determine the linear amplitude of pregalactic perturbations which is by no means measured in the CBR due to the strong Sunyaev-Zeldovich effects in galactic scales. If one has the amplitude of linear density fluctuations at galactic scales, one can not only set the initial condition for galaxy formation, but also make more reliable determination of cosmological parameters.

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